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Development of a Water-Filled Conical Shock Tube for Shock Testing of Small Sonar Transducers by Simulation of the Test Conditions for the Heavyweight Test MIL S-901D (Navy)

by

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A small conical shock tube is being used to provide an inexpensive alternative to standard explosive shock tests presently performed in open water at a commercial testing facility. The conical geometry was chosen because it represents a small solid angle segment of the spherically expanding field in open water. The charge required to produce a specified shock-wave pressure in open water is reduced by the solid angle. The test transducer is mounted to a piston located in a cylindrical chamber at the large end of the shock tube. The shock wave from the explosive propagates down the conical tube and strikes the transducer, producing the pressure shock. The expanding gas bubble from the explosive then accelerates the piston along its tube, resulting in an inertial shock. Extensive testing was performed to establish a proper breech design, and to determine the amount of water tests. A list of alternative pressure-measurement gages that were considered is discussed, and qualitative results are given. Pressure-shock waveforms and resulting displacements are presented for the shock tube and compared with similar measurements form open-water tests.

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DEVELOPMENT OF A WATER-FILLED CONICAL SHOCK TUBE FOR SHOCK TESTING OF SMALL SONAR TRANSDUCERS BY SIMULATION OF THE TEST CONDITIONS FOR THE HEAVYWEIGHT TEST OF MIL S-901D (NAVY)

INTRODUCTION

In 1983, the Naval Research Laboratory's Underwater Sound Reference Detachment (NRL-USRD) obtained a small (6-in diam) shock tube from the University of Central Florida (UCF). The shock tube had been designed and built by UCF as part of a research contract with NRL to perform preliminary shock tests on fiber optic feed-throughs used in submarine hull penetrators.

A few words to place the shock tube in historical perspective are in order at this point. According to Coombs and Thornhill [1], the development of explosive-driven water-filled wave guiding devices began in Europe about 1957, when underwater explosive guns used for stunning fish were first reported. Coombs and Thornhill described a conical-sector underwater shock gun in their theoretical study, but they were largely concerned with diffraction of the shock wave after it left the tube. Their report was published originally in 1958, but because of possible military applications, it was not published in the open literature until 1967. In the meantime, W. S. Filler, of the Naval Ordnance Laboratory in the United States, was developing conical shock tubes and measuring the shock wave pressure signatures inside the expansion cone. He worked first with an air-filled tube [2], then with a water-filled tube [3] The latter tube was the basis for the design of the USRD shock tube.

We planned to develop the shock tube as an alternative means for testing certain sonar transducers that are required to pass a standard underwater shock test. This test, known as MIL-S-901D [4], generates both pressure shock wave and inertial shock environments for exposing the subject transducers In the test, the transducer, usually along with many others, is attached to the bottom of floating shock platform (FSP) and explosive charges are detonated near the platform in a prescribed series. The charge specified is 60 lbs of HBX-1 detonated at a depth of 24 ft below the surface. A charge is detonated at horizontal distances of 40, 30, 25, and 20 ft from the near side of the FSP.

The University of Central Florida had made no attempt to simulate inertial effects in the tube, so they used it with the end closed by a rigid plate. In our planned use of the shock tube, the transducer to be tested would be mounted to a sliding piston located in a cylindrical chamber attached to the large diameter end of the shock tube. The shock wave resulting from the explosion would propagate down the conical tube, strike the transducer, and impart the pressure shock The expanding gas bubble from the explosive would then accelerate the piston along the cylindrical tube, resulting in an impulse, or inertial shock, to the transducer A pressure measurement probe, or shock gage, would be mounted near the transducer to monitor the shock wave pressure during the test

Figure 1 is a photograph of the USRD shock tube set up for operation In the foreground, the breech is opened, as it would be for loading the explosive charge. A charge is placed in the small cavity in the breech block which is seen lying on the platform. Electrical leads that run the length of the tube are connected to a detonator in the charge. These leads emerge through a sealed connector at the far end of the tube. Leads for the pressure measurement gage also are brought out at the far end.

A cylindrical section seen hanging from the hoist sling holds the piston slider, which is not shown in this view.

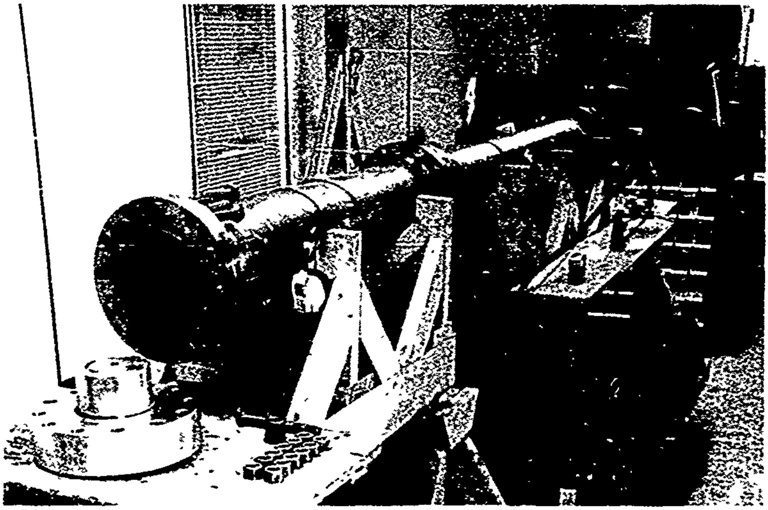

Fig. 1 - The USRD shock tube.

THE TUBE

The conical geometry of the shock tube may be considered to represent a small solid angle segment of the radially expanding field resulting from the detonation of a small sphere of explosive in open water. If the rigid walled tube is thought of as confining the expanding pressure field, then the original sphere of explosive may be replaced by the small conical sector of explosive within the apex of the cone. Figure 2 is a diagram representing this concept.

When comparing the shock waves produced in the conical shock tube to those produced in open water, one may derive an amplification factor based entirely on geometry, or one may calculate a practical amplification factor based on the measured shock wave pressure amplitudes in the two cases. A theoretical amplification factor (AF) for a conical shock tube may be provided by the ratio of the volume of the sphere of explosive to the volume of the small conical sector of explosive. This ratio is equivalent to the ratio of the solid angles of the sphere (4π) and the sector [$2\pi(1-\cos\alpha/2)$], where α is the plane angle of the cone. This figure may be expressed more simply as

$$AF = \frac{1}{\sin^2(\alpha/4)}. \qquad (1)$$

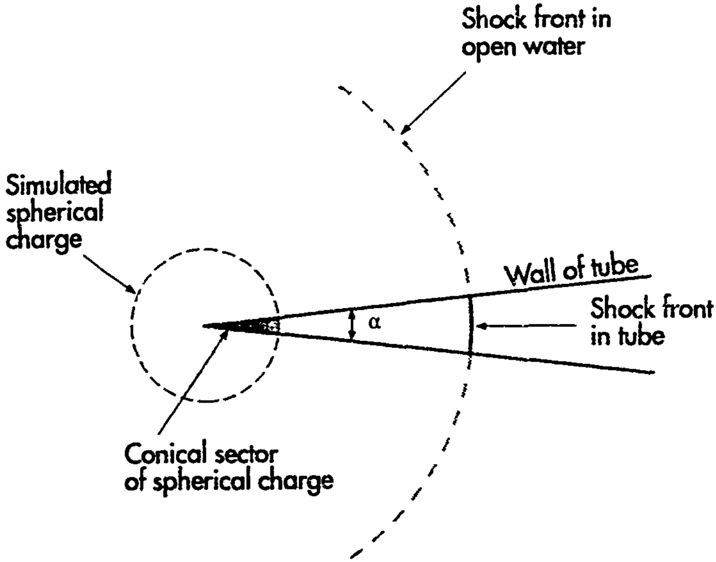

Fig. 2 - Amplification of explosive charge in shock tube.

The calculated value of AF for the USRD shock tube is 7770. A measured performance factor is given by the effective weight amplification. If a spherical charge of weight W is required in open water to produce a peak pressure equivalent to that produced in the shock tube by a charge segment of weight w, then the effective weight amplification may be expressed as W/w. Values computed from measurement data give 2076 when the charge, w, is an E-1A(8) blasting cap, and 1214 when the charge weight is 6.25 g (1.38×10^{-2} lb) of DuPont Detaprime® with an E-1A(8) detonator. The decrease of performance with charge weight is thought to be an effect of elastic deformation losses in the shock tube vessel.

One of the first problems encountered with the shock tube was caused by sound propagated down the steel walls of the tube and reradiated into the water. The result was a distorted shock wave pressure waveform. We attempted to improve the waveform by discouraging that propagation path Gaskets were placed between the flanges at the central joint, at the end plate, and at the breech. More attenuation was obtained if the bolts clamping the flanges were also isolated with rubber washers and sleeves, but blowouts occurred frequently. Gaskets alone improved the measured waveform of the shock wave, but still reduced the integrity of the joints, especially at the breech end A series of test shots was done with accelerometers (PCB type 305A) mounted to the flange faces of the tube. The propagation velocity of the sound in the steel was confirmed to be about 5050 m/sec. The peak-to-peak acceleration at the tube's center flange was about 170,000 g, where g is the acceleration due to gravity. The attenuation across the center flange was 8.5 to 10 dB with gaskets and 1 to 1.5 dB without gaskets. As the wave progressed down the tube, energy collected in resonant modes, such that a 3-kHz component dominated the spectrum at the plate sealing the test (large-diameter-bore) end.

THE BREECH

The original breech held a charge intended to simulate a conical sector of explosive at the apex of the conical tube. A practical approximation to the conical sector was a squat cylindrical cavity of about 2.5 cm diam and nearly 2.5 cm high. Rapid deformation was a major problem with the breech cavity, and fracture of the breech block was the eventual result. The breech held a DuPont E-1A(8) electric blasting cap as the detonator, and up to 6.25 g of DuPont Detaprime® G, a booster, as the main charge. The charge weight was varied depending upon the peak shock wave pressure desired.

When we began the shock tube project, we quickly discovered that a considerable amount of work would have to be done first to develop a reliable blast gage and to improve the waveform of the shock wave in the tube. At that point, we decided to do most of the experimental measurements using blasting caps, rather than larger charges of plastic explosive. After the measurements were refined, and the desired pressure levels for formal tests determined, we realized that blasting caps alone gave peak pressures that were almost high enough. The increased pressures of larger charges could accelerate component failures in the tube unnecessarily.

The initial occurrence of a breech fracture happened on the last shot of a test series during our first application of the shock tube. It was quite spectacular and somewhat humorous. Laboratory space was crowded, and at this time one of our colleagues had moved into the shock tube building to make some measurements in a small moveable tank which included a rack of electronic equipment and a small computer. During the shot, safety regulations required him to move into an adjacent room along with the shock tube operators. When the breech block ruptured, one of the bolts securing it to the backing plate was sheared off. The broken bolt flew across the room, closely followed by a strong stream of foul-smelling, inky water. Unfortunately, our friend's electronic rack with computer was directly in line and suffered a drenching. Amazingly, his equipment was gone from our space within 15 minutes after the incident. The accident did cause us to give some thought to reorienting the shock tube for increased safety. We subsequently turned the tube end for end, so the breech end was located near an outside wall rather than in the center of the room.

The incident of the breech block fracture related above resulted in a period of intense activity which included a redesign of the breech block, a series of experiments to find a better breech block material, and a fracture analysis study [5] of breech block failure. The study analyzed the deformation and fracture of breech blocks made of AISI 1018 steel, AISI 4340-300M hardened and tempered steel, and AISI 4340-300M untreated steel. We immediately applied two recommendations made in this report [5]. First, the bolt holes in the breech were eliminated. The problem of distortion and fracture in the original breech block was being aggravated by the original design in which the breech block was bolted to the breech backing plate. This arrangement required tapped holes in the breech block. The holes were sites of stress concentration. We changed the design so that the breech block was clamped in place by the backing plate. The integrity of the breech assembly was now much greater because the holes were eliminated. In the second recommendation, a resilient neoprene pad was placed between the breech block and its backing plate to provide slight recoil space for the breech block. This modification has not been completely successful. The motion of the breech block allowed by compression of the resilient backing causes some instantaneous leakage at the breech. This leakage promotes erosion and distortion of the adjacent parts, and almost guarantees destruction of the breech block face O-ring seal on each shot. Figure 3 is a photograph of the breech end of the shock tube showing distortion from repeated shots.

Fig. 3 - (top) Breech face of shock tube after 3 full-charge shots.
(bottom) Breech face of shock tube after 15 full-charge shots.

As other materials were obtained, more breech blocks were made and tested The S5 tool steel showed low deformation and very early fracture Aluminum-bronze deformed to the point of being unusable, but never fractured. The 316L stainless steel and titanium were also tested. Titanium gave the longest useful life. The conclusion reached concerning materials was that, since no material exhibited durability sufficient to insure what might reasonably be called a long life, the most cost-effective material, including fabrication and cost per firing, was 1018 steel.

The large number of firings required for the breech block testing had an adverse effect on the mouth of the conical shock tube section at the breech end The surface that mated to the breech block was deformed inward, matching the outward deformation of the breech block The tube bore there was also somewhat enlarged, although not as much as the breech blocks, and the tube face was highly pitted. A deep longitudinal fissure about 1 in. long had formed on the upper surface of the bore A section of the tube was machined out and a bushing of aluminum-bronze, with diameter of about 3 in., was pressed in to renew the tube face and bore Aluminum-bronze was chosen because, at that time, our intention was to use that material for a large shock tube which was being planned This was an experiment to test the material's performance in the high-pressure area of the shock tube Figure 3 shows the result of this experiment The new surface started to deform and pit almost immediately with resumed firing, indicating that periodic replacement of this section, in addition to the breech block, might be necessary.

The University of Central Florida designed and built a modified breech assembly for the shock tube which was intended to improve the waveform of the shock wave and increase the longevity of the breech. It was called a "distributed" breech, presumably because it used a distributed charge of explosive in sheet form, rather than the original compact charge shape. The distributed breech contained a cavity about 2½ in across by 1½ in deep. Its diameter was dictated by the size of the conical section of the shock tube at the first flanged joint, where it was to be attached The explosive charge was a circular disk cut from a sheet of DuPont Line Wave Generator.

The Line Wave Generator is a flexible sheet explosive made in the form of an equilateral triangle 10.9 in. on a side, with hexagonally spaced circular perforations throughout The material is designed so that a detonation initiated at any apex of the triangle will reach the opposite corners at the same time. The disk of explosive used in the distributed breech was initiated at its center with a DuPont E-106 blasting cap, a small device specifically developed to detonate sheet explosive. To cut up and use such an elegant material in a way that ignores its special properties seems completely inappropriate.

We were unable to compute an effective weight amplification factor for the distributed breech because the distributed shape of the charge makes the concept, which is based on spherical charges, invalid. Published information about TNT-equivalent weights for the E-1A(8) blasting caps and the Detaprime® booster was not available, and data on the ingredients and composition had to be obtained from the manufacturer's representative and used to compute TNT-equivalents.

In loading the tube, it was difficult to manipulate the distributed breech onto the shock tube while keeping the detonator centered in contact with the disk of explosive A large piece of putty was used to secure the detonator. Figure 4 shows a charge in the distributed breech. This method was unreliable and generated a quantity of contaminating combustion by-products in the tube. The waveform was not improved by the distributed breech, so the original breech was returned to service, and the shock tube was restored to its full length

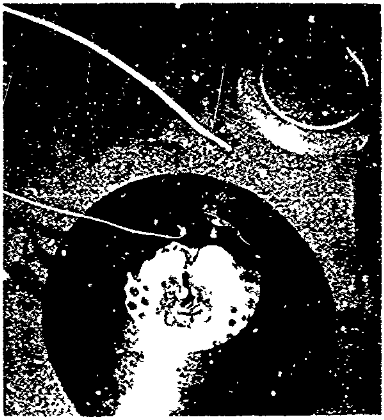

Fig. 4 - Distributed breech with charge loaded

The original compact breech also had a problem in centering and holding the charge in the breech block cavity when an electric blasting cap was being used alone as the charge. An experimental breech block was made with the charge cavity diameter reduced from 1 in. to about 5/16 in. This allowed the blasting cap to be stuffed into the hole with the crimped end first and the leg wires alongside the cap's body in the hole. The wires provided enough friction to keep the cap in the hole. However, after only a few shots, the edges of the hole appeared to be deforming and eroding badly. The next modification was to taper the sides of the hole at a 200° angle for a little more than half its depth. The mouth of the hole was about 15/16-in. in diameter, but the strange shape of the charge cavity created by these designs made using larger charges impossible. A short time later we developed a suitable solution by returning to the original breech block cavity and holding the blasting cap in position with a thin, circular piece of rubber about ¼ in. thick and 1 in. in diameter which sealed the cap in the hole. The rubber ring was slid part way over the cap, and the cavity filled with water. The cap and ring were then pressed into the hole. Figure 5 shows a cap being rigged in this manner. This combination had no adverse effect on the shock wave waveform and stayed in position reliably while the breech was bolted onto the tube, and the tube filled with water. The ring usually survived for several shots, and was easily replaced.

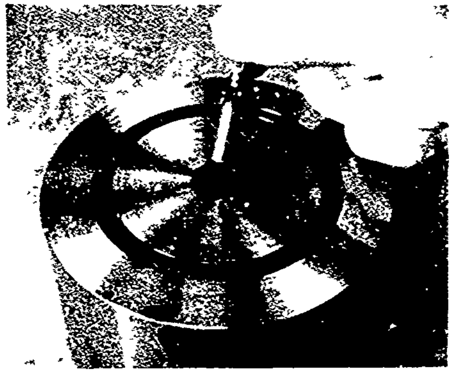

Fig. 5 - Loading blasting cap in breech block with rubber disc.

THE GAGES

We began working with the shock measurement gages, which were tourmaline-disk 'Woods Hole' type that had been obtained from the Naval Ordnance Laboratory (NOL) These gages are similar to the "Type B" gages described by Cole [6] Most of the gages had required repair during the work done at UCF, and the repairs were done at USRD.

The transient response characteristics of tourmaline disk gages have been extensively studied and documented over the years Cole [7] explains the preference for orientation of the tourmaline disks perpendicular to the pressure wave front He also shows how the gage output may be corrected for the integrating effect due to the transit time of the pressure wave front across the disk face. This essentially consists of extrapolating the gage voltage output back in time to the point where the wave front crosses the gage center This is approximately equal to one-half the rise time of the transient signal at the gage output. A slightly easier to read version of the discussion is given by Arons and Cole [8].

Gage Problems

Two problems were immediately apparent when these gages were used in the USRD shock tube: with a closed tube, the gage cable extruded through the rubber gland seal used to bring the cable out through the shock tube end plate, and frequently after a shot, bubbles appeared in the silicone oil inside the gage boot.

The original gage mount developed by UCF was a brass tube which extended from a threaded hole in the center of the plate that sealed the test end of the shock tube. The gage cable was fed through the brass tube with the gage resting on the edge of the brass tube (The 'muzzle', or large end, of the shock tube is normally the test area. We call it the test end to distinguish it from the breech end, which contains the explosive.) The diameter of the gage was larger than that of the brass tube, so the gage was unable to pass through the brass tube. The brass tube was screwed into the plate, and the cable exited through a rubber compression gland. Figure 6 shows the original gage and mount. When the explosive was fired, as much as 4 in of cable was extruded through the gland, sometimes decapitating the gage, or cutting the cable. We eventually solved this problem by removing the gland and using a sealed underwater connector on the plate. The gage cable was shortened and a mating connector was molded onto the end. The connectors gave no reliability problems thereafter. The gage mount was changed from the UCF tube design to a separate cage which slipped into the bore of the tube and suspended the gage in the center of the tube by thin rods. Figure 7 shows the cage.

Another improvement was effected by discarding the oil-and-boot packaging method and molding the tourmaline crystal stack in Rho-C material. This eliminated the bubble formation problem and greatly reduced the tendency of the crystal stack to split.

The durability of the tourmaline gages has been increased to the point that the gages are considered usable, if not completely reliable, as far as blasting cap measurements in the tube are concerned. The gages still may suffer failures when subjected to large accelerations perpendicular to their axis of symmetry.

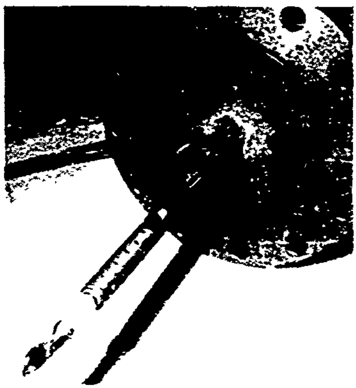

Fig. 6 - Original gage and mount.

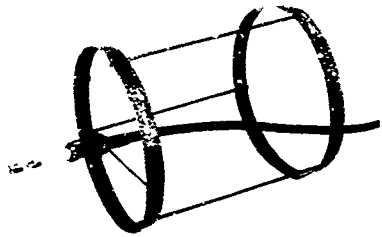

Fig. 7 - Shock gage with cage-type mount.

Shock Wave Measurements

Shock waves measured in the tube showed peaks that were rounded. This effect seemed to be a characteristic of the tube. Figure 8 shows a typical shock wave pressure signature from the shock tube. The high-frequency energy which has a strong visual effect on the appearance of the pressure-wave signature does not contribute much to the total energy in the spectrum and seems to be characteristic of a shock wave generated in a conical tube with thick steel walls. This signature may be compared to Fig. 9, which is an open-water pressure signature at a range of 30 ft, recorded during a MIL S-901D test at the West Coast Shock Facility, in San Francisco, CA. The most prominent difference is the "steel" signal in the shock tube trace which was mentioned above. The sharp peak at the top of the open-water trace appears rounded off in the shock tube trace. Working on this problem caused us later to return to the distributed breech as a way to look at shock waves generated in a tube of different geometry. No difference was found in the shape (i.e., rounded) of the shock wave peak in the shortened tube. Using the distributed breech with non-distributed charges (i.e., blasting caps) produced waveforms that were considerably more distorted than those produced with the full-length tube and the original breech block.

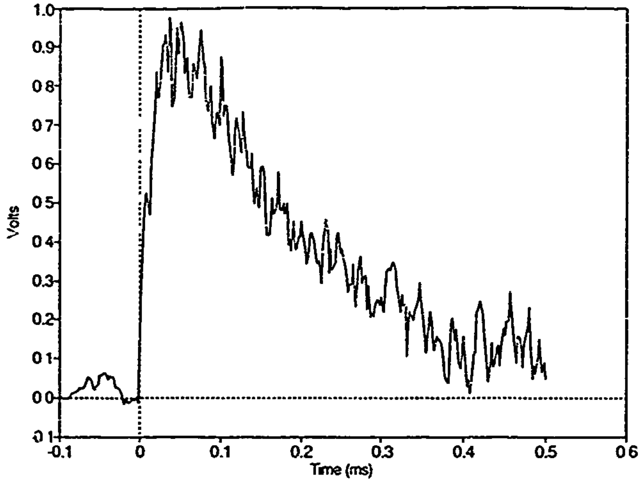

Fig 8 - A typical shock tube pressure waveform.

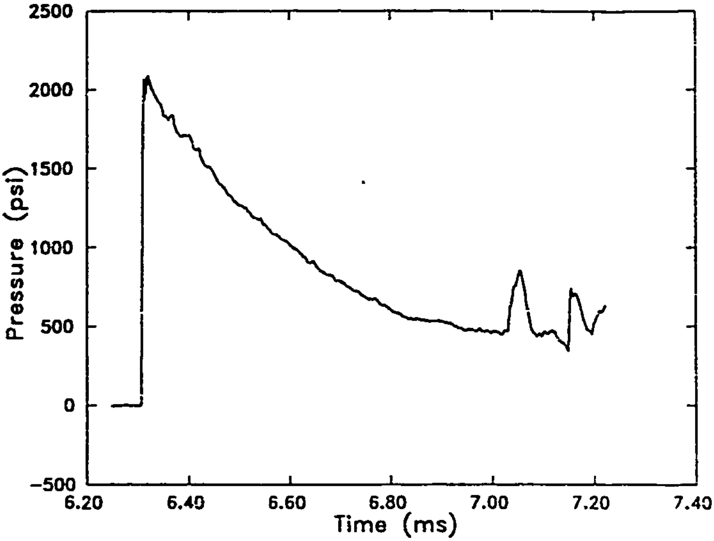

Fig. 9 - Pressure signature from 30-ft range open-water test shot at West Coast Shock Facility.

To examine the shape of the wavefront across the shock tube we used two gages. Measurements were made with the gages situated in a plane, one on the tube axis and the other near the tube wall. The waveforms measured at the wall of the tube appeared normal (i.e., rounded). We found that the shock front at the wall trails by no more than 2 mm from the center. The peak is rounded with an amplitude of about 10% less than at the center. The gage measurement position was moved from a point approximately 25 cm from the test end to a point near the middle of the tube's length. Again, it was found that the shock wave in an earlier stage of propagation (i.e., nearer the source) had a rounded peak. The plane shock wave does not interact with the tube wall to a degree that causes much distortion of the wave front, and the rounded peak of the shock wave appears to be a characteristic of the tube itself.

On several occasions we were asked to expose small (approximately 4 x 4 in.) hydrophones to shock waves of a specified peak pressure (from 2000 to 3000 psi) in the tube. We were able to do this by adjusting the charge weight.

In the process of making a sequence of shots with gradually increasing charge weights to adjust the peak pressure, the breech block was changed to one made of a different material. At that point, we observed a change in the shock wave peak pressure that led us to question how much of the explosive energy product was being lost in the metal walls of the tube. A very long series of experiments was launched to determine, in a crude, qualitative way, how much the walls of the shock tube were deflecting as the shock wave passed. Several bonded-type strain gages were mounted on the tube after much time was spent checking the strain gages for operability. When it was determined, using basic principles, that the strain gages were indeed capable of recording deformations, they were mounted on the shock tube. No sensible output was ever seen that would represent deformation of the shock tube surface in any mode. The experiment was discontinued

Gage Calibration

We were developing measurement techniques and making measurements concurrently, and early on we developed a technique for obtaining calibrations of the gages. A rigging bar was built so that a blasting cap could be mounted at a fixed distance from a clamped and oriented gage at any time in the open water of the lake. This procedure yielded a repeatable, clean exponential waveform (such as that seen in Fig. 10) from which we could compute a pressure calibration using the charge weight of the blasting cap and the scaling equation for TNT [9]. Because of the difficulty in getting information on the base change composition, it was a long time before we finally obtained an accurate figure for the TNT-equivalent charge weight of the blasting caps. We finally settled on a figure of 10.08 grains TNT-equivalent weight for the E-1A(8) blasting caps being used. By this time, there were available waveform digitizers of sufficient speed and precision to capture the shock wave signature with accuracy. The procedure for processing the waveform data into a calibration consisted of first estimating the baseline value of the signal and normalizing the data to that value. Then, beginning at the peak value (see Fig. 10), data points were used up to the time where the decaying signal no longer looked exponential because of bumps or wiggles that distorted it. This usually occurred at an amplitude about one-half to one-third of the peak. These data points were used with a least-squares curve-fitting process to fit an exponential of the form $e^{-\alpha t}$ to the data. The fitted exponential was then evaluated at a time equal to one-half the risetime of the data curve (baseline to peak). This estimated value was taken to be the voltage output of the gage produced by the peak pressure of the shock wave when corrected for the finite gage size. The peak pressure of the shock wave at the gage-to-blasting cap distance was computed from the scaling equation for TNT

$$P_{pk} = 21{,}600 \left(\frac{W^{\frac{1}{3}}}{R} \right)^{1.13} , \tag{2}$$

using the cap's charge weight. P_{pk} is the peak pressure in psi, W is the charge weight in pounds, and R is the range in feet. A calibration in either dB/V/μPa or mV/psi could then be computed. Several gages were also calibrated by measuring the charge produced by increased hydrostatic pressure. This was done using the 16-in. projectile pressure vessel and a Keithley 610C electrometer. The results were not encouraging. All the gages but one had problems, either from internal electrical leakage or other unknown causes, that prevented us from obtaining reliable results from the measurements.

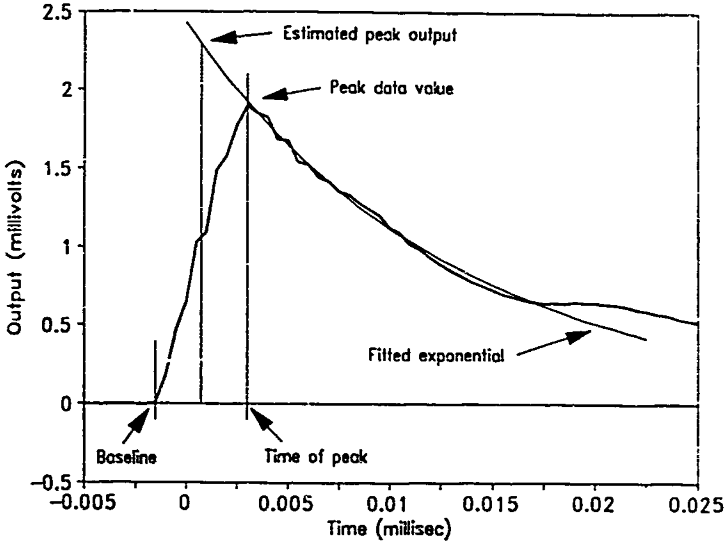

Fig. 10 - Estimating shock wave peak from gage output.

Tests of Alternate Gage Types

Because the gages for measuring the shock wave pressures always gave problems, we were steadily looking for other options. Numerous alternative gage types and configurations were tested as they were obtained. We had built a new tourmaline blast gage with the same basic design as the first, but using a crystal stack of 0.150-in. squares. The original gage was a stack of ¼-in. circles (Fig. 11). We felt that this second gage of smaller dimension should exhibit slightly shorter rise time and higher frequency response.

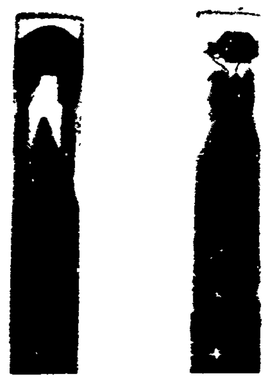

Fig. 11 - Two tourmaline measurement gages: ¼-in 'Woods Hole' type (left), and 0.150-in -square stack (right).

Flush-mounted quartz pressure gages manufactured by Kulite were tried, but their output was so low using our standard calibrating shot that no output could be recorded These gages were of extremely low sensitivity and, although their resonance was listed as 395 kHz, we doubted that their high frequency response would be useful.

We had been given one of the few surviving examples of a subminiature barium titanate hydrophone made at Raytheon Corp. in New London, CT, after a design by Romanenko [10] The construction of Raytheon's version is described by Konrad and Abraham [11]. We tested this hydrophone's response to the shock wave stimulus and found it to be excellent, although it was relatively insensitive. In 1985, USRD attempted to replicate and improve, if possible, the Raytheon hydrophones. The project was cancelled after two successful hydrophones had been made (see Fig. 12). Unfortunately, these hydrophones were never tested to assess their shock wave response, possibly because they seemed too fragile to survive use in the shock tube. A description of the construction technique which was developed is documented by Zalesak and Poché [12]

Fig. 12 - Subminiature Barium Titanate hydrophone.

Another subminiature pressure probe tested was the Dapco needle transducer type NP10-1. This is a pressure probe designed for medical ultrasonic use that has a 0.025-in.-diam active element housed in a 19-ga hypodermic needle. The response was found to be very peaky and, although possibly suitable for continuous wave measurements, it would not be useful for broadband transient recording. It proved to have a low-frequency sensitivity of -254 dB re 1 V/μPa when calibrated at 1.2 kHz. This transducer also was not tested directly for shock wave response.

A 1/8-in.-diam tourmaline gage was tested. This transducer is the Series 138A manufactured by PCB Piezotronics, Inc. The transducer crystal is booted in oil in a clear vinyl tube with a built-in line driver amplifier. Several maximum pressure range versions are manufactured. The model we obtained (138A10) is designed for 10,000 psi. Its sensitivity is approximately 0.5 mV/psi, which is about -263 dB re 1 V/μPa in acoustical units. This transducer seems to come closest to meeting the requirements of shock tube use, except for one major drawback. As previously noted in Cole [7], tourmaline disk gages cannot be made physically small enough to give a good representation of the rise time of the shock wave. Orientation is critical in measuring small charges with small gages. When the gages' highest frequency mode is driven, their output is largely underdamped, so orientations are avoided that would allow the shock wave to excite this mode. The preferred orientation is with their longest dimension parallel to the direction of propagation of the shock pressure wave. The PCB gage's tourmaline element is covered with a braided shield and the entire crystal assembly is suspended on flexible wires. So not only is it impossible to see the crystal stack to tell which way the disks are oriented, but it is unlikely that the crystal stack will remain oriented when the gage is moved. The PCB transducer is intended to be used hanging vertically on a cable, with gravity centering the crystal element. When mounted horizontally, as in the shock tube, the sensitive element tends to lie against the bottom of the boot tube, depending somewhat on the stiffness of the braided shield. We devised a cage assembly to mount the PCB gage horizontally in the shock tube. Figure 13 shows the PCB gage mounted in its cage. When tested with our calibration procedure in open water, the gage gave variable waveforms, probably because of the orientation problem mentioned above.

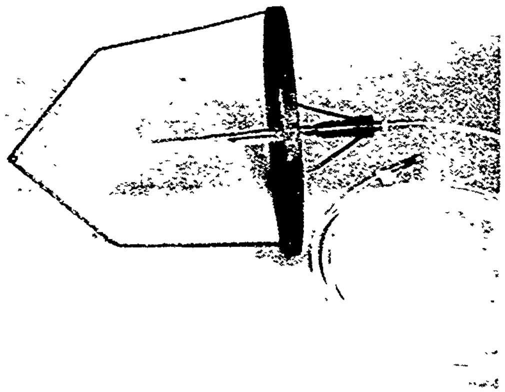

Fig. 13 - PCB model 138A10 tourmaline gage mounted in cage-type fixture.

Two other gages of different form were tested. These were manufactured by Dynasen Inc. and are intended for measuring shock wave transmission in solids. The first was a piezoresistive gage that was designed to be connected as one arm of a balanced bridge circuit. The piezoresistive element was made of ytterbium metal deposited as a square grid on a flexible plastic (Kapton) substrate. We oriented the gage with its large dimension parallel to the shock wave front. This is opposite to the customary orientation of the crystal gages, but this gage is extremely thin in the thickness dimension and its resonance is probably far above the maximum frequency we record Physically, the gage resembles a strip of Scotch tape and presented problems with mounting and electrical connection We decided to address the mounting problem by cementing the gage to the base of a cone-shaped piece of brass, the idea of the cone being that its shape would suppress any resonant modes generated by the shock wave in the metal The problem of connecting leads to the gage was treated by soldering wires directly to the copper-foil leads on the gage. It was reasoned that since the gage was being cemented to the brass cone, soldering leads to it didn't matter, because changing the mount would probably destroy the gage anyway. This turned out to be a correct assumption. The Dynasen piezoresistive gage is shown being tested in Fig. 14. A low-impedance bridge circuit was constructed and, with careful shielding of the gage leads, a low-noise recording could be made. The rise time of the gage was short indeed, but the gage output corresponding to the decay portion of the shock wave signature always appeared to have a large negative voltage swing that cut off the exponential decay much too quickly.

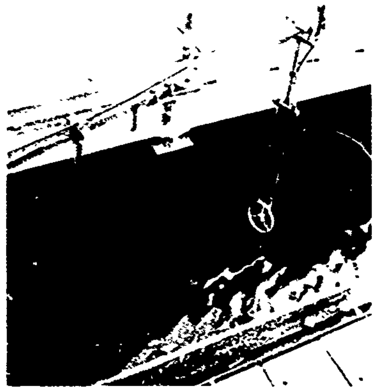

Fig. 14 - Dynasen piezoresistive gage rigged for shock testing.

The second type of Dynasen gage was a PVDF piezoelectric transducer built in the same form as the first, consisting of a thin square of the active plastic bonded to the Kapton substrate. We decided to try to mount and connect the gage in a nondestructive manner for this trial. A small, sealed polycarbonate clamp was built which connected a low-noise cable to the gage with spring finger contacts. The gage was first tried without an "anvil" block, but no good waveforms were recorded this way. A great deal of ringing at 67 kHz was present in the recorded output. The output sensitivity computed from Dynasen's published figures is -291 dB re 1 V/μPa. The sensitivity we measured was -250 dB re 1 V/μPa. A second trial was made using a lead cylinder as an "anvil" block. The cylinder's dimensions were 3.25 in. diam by 3 25 in. high. The gage was bonded to the block with soft wax. Figure 15 shows the Dynasen PVDF gage and mount. Once again, the recorded output contained the negative overshoot that the piezoresistive gage exhibited.

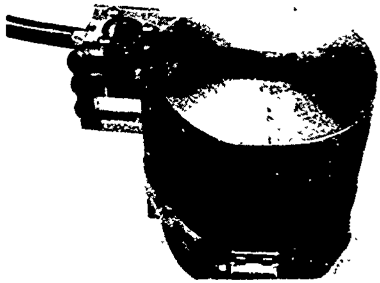

Fig. 15 - Dynasen PVDF piezoelectric transducer mounted on lead block.

Another type of piezoresistive transducer was tested. This was an Endevco Model 8511A-5K, a pressure transducer apparently intended for use as a static pressure or low-frequency transducer. It was built with a threaded mount, so we assumed it was an engineering-type transducer. The gage was mounted 10 cm from a blasting cap and its output was recorded in both normal incidence and parallel incidence orientations. The results were not good enough to warrant further investigation.

The gage type that performed best for us was a modification of the original gages we inherited from the Naval Ordnance Laboratory. It is similar to the Type B tourmaline disk gages described earlier. The principal improvement we made was to remove the oil-filled boot and mold the gage in Rho-C compound. The Rho-C envelope is roughly the same size and shape as the original vinyl boot, and the Rho-C is transparent enough to allow us to inspect and orient the gage visually. These gages continue to be subject to the principal failure mode of the tourmaline gages -- fractures in the cemented crystal stacks and debonding of the electrodes. The original gages were constructed with two of the electrodes made of sheet copper, one for each terminal. Other electrodes in the stack were made of foil and connected with fine soldered leads. The sheet copper gave the crystal stack the necessary mechanical support when the gage was oil-filled. When we decided to mold the gages in Rho-C compound, support for the crystal stack was no longer needed. So, when the crystal stacks were rebuilt, the copper sheets were usually replaced with foil, and fine wire leads were used to connect the entire stack. The original stacks with copper electrodes seemed to survive much longer in use, however. Sensitivity for a typical ¼-in, 4-crystal stack is about -252 dB re 1 V/μPa.

RECORDING EQUIPMENT

From the beginning, we have used a Nicolet Model 2090 digital storage oscilloscope to record the output from the tourmaline gages. Its maximum sampling frequency of 2 MHz and 12-bit amplitude resolution are just sufficient for recording the gage output, which is normally in the range of 1-10 V. This is fortunate because the Nicolet's preamplifiers lose accuracy at high frequencies when used at the maximum gain settings. Its input impedance is relatively low (1 mΩ) for direct input from the tourmaline gages. The Nicolet oscilloscope is quite portable and needs no computer controller. Its recorded waveforms may be stored on floppy disks and transported to a desktop PC for processing after format conversion. Its only inadequacies consist of a rather primitive triggering control and somewhat small (by present standards) memory size. Early in 1986, we tried increasing the effective input impedance of the Nicolet oscilloscope. The gage and its low-noise cable, including the connector through the shock tube wall, measured about 1100 pF capacitance. Of this, the cable and connector accounted for 960 pF. The Nicolet oscilloscope input impedance was 1 mΩ. All attempts to use preamplifiers to raise the input impedance were unsuccessful because the large gage output would overdrive the input stage of most preamplifiers. We tried using a Tektronix 10x oscilloscope probe as a passive attenuator. It could be adjusted for optimum waveform and gave an input impedance of 10 mΩ. The low-frequency part of the waveform was much improved, so this arrangement was adopted as the standard gage input for the Nicolet oscilloscope.

FURTHER APPLICATIONS

Several procedures were found to be necessary to obtain consistent and repeatable shock wave measurements. The first was to degas the water in the shock tube before firing by applying a vacuum to the vent port after the filling port was closed. A water aspirator pump was used for this purpose. Figure 16 shows a schematic diagram of the shock tube plumbing. Second was the "rubber stopper" technique described earlier for centering the blasting cap in the water-filled explosive well of the breech block. Third was to apply positive water pressure to the tube before firing. This procedure was possible only when the reaction chamber and slider were not used, and the tube could be sealed with a rigid plate. To do this, the filling port was reopened after the degassing was completed and the valve reclosed with approximately 50 psig water line pressure in the tube. After the firing, the tube was emptied by applying air pressure at approximately 100 psig to the vent pipe and exhausting the water through the drain.

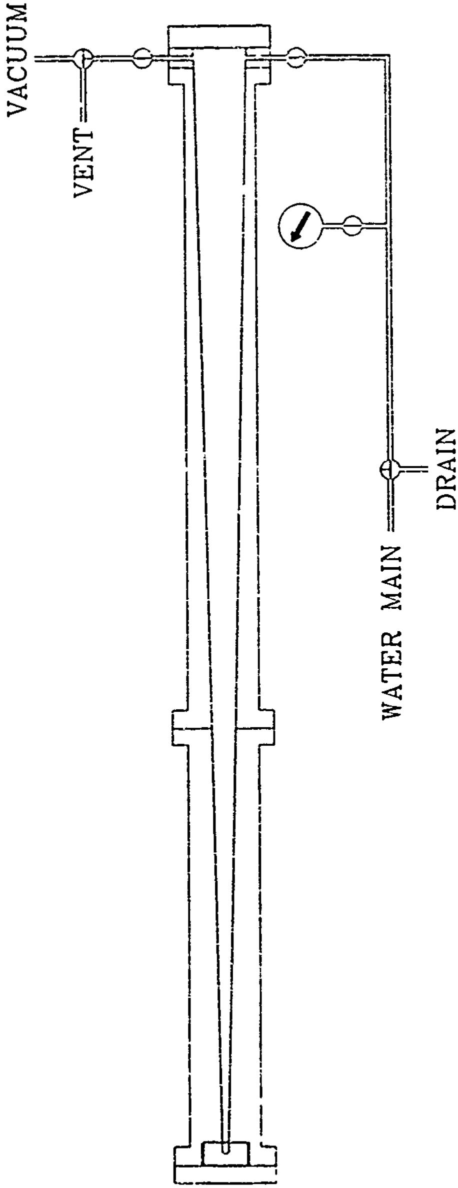

Figure 16. Schematic diagram of shock tube plumbing.

ABSORBERS

In February 1984, we began to study the requirements for using a shock tube to duplicate the conditions of the MIL-S-901D shock test as performed by the West Coast Shock Facility. Individuals at other Navy laboratories had expressed concern whether devices under test in the tube would be exposed to multiple shocks because of the in-phase reflections from the steel end plate and other surfaces. We felt the end plate reflection would not be difficult to control because of our experience with reducing high-frequency echoes using saturated cypress blocks in dolphin tanks [13]. Accordingly, we build a short cylindrical extension tube about 2 ft long for the test end of the shock tube and pressed in a piece of grain-oriented cypress which had its end tapered so that is resembled a giant wood pencil. This wood had been saturated by pressure-cycling several times to 1000 psi in a water-filled pressure tank. This modification caused the end-plate reflection of the shock wave to be reduced by about 13 dB at the gage position. No shock is reflected from the breech end because the expanded gas bubble from the explosive prevents a shock reflection.

INERTIAL MEASUREMENTS

The "reaction block," or slider, was necessary as a mechanism for holding the device being tested in the shock tube. Our hope was that somehow the slider's motion could be adjusted to match, along one axis, the inertial motion of the FSP for the MIL-S-901D tests. A cylindrical tube, whose diameter is slightly larger than the exit diameter of the conical shock tube, was bolted by flanges to the end of the conical section. Inside, free to slide, is a piston made of two solid disks spaced apart by three rods. The piston face nearer the shock tube end serves as a mount for the test device and seals the water in the tube. The opposite face is open to the air. By sealing the open end of the cylindrical tube, the volume of air behind the dry side of the piston may be pressurized or evacuated as required to adjust the motion of the piston. The slight step in the diameter between the conical shock tube section and the cylinder section provides a mechanical stop for the piston when the water is being degassed. We first thought we could record the slider motion using an accelerometer on one of the piston faces. This was not possible because the frequency of the slider motion was much too low for the sensitivity of the standard size accelerometers. We finally used a 20-in. linear variable differential transformer (LVDT) to record displacement. The core of the LVDT was attached to the dry piston face of the slider.

We modelled the slider motion as a damped simple harmonic oscillator with mass formed by the slider and the water in the shock tube. The spring was composed mainly of the gas bubble of explosion by-products. The initial trial to measure slider motion used air pressurized at 50 psig in the back volume of the slider chamber. This increased the spring stiffness of the oscillator. The FSP inertial motion we were attempting to reproduce with the slider may be approximated by a half-sine pulse of 16-in. peak displacement and 600-ms duration. The peak velocity should be near 11 ft/s. With a blasting cap alone as the charge, the observed slider motion proved to be too low in amplitude with too short a period (2.3 in. and 88 ms). Next we tried opening the back volume of the slider chamber to eliminate that portion of the spring stiffness. This gave an increase in both the amplitude and period of the slider, but still not enough (7 in. and 350 ms). The next trial added 1.0 g of Detaprime GA to the charge. The period was virtually unchanged, but the amplitude increased to more than 16 in., causing the slider to strike the stop we installed in the cylinder to prevent damage to the LVDT. We were able to compute some rough values for the spring constant with the data from these shots and the tube dimensions. Then we recomputed the oscillator parameters required to give the desired motion. This called for increasing the mass of the slider/water combination by a factor of four. We decided to add about 200 lb to the slider. A lead weight was cast in cylindrical shape and clamped between the piston faces. We then obtained a period of 550 ms, an amplitude of 15½ in. and a peak velocity of 11 ft/s by using a charge consisting of the E-1A(8) cap plus 0.7 g of Detaprime with the 200 lb of added weight. Thus, we can accommodate a transducer weight of up to 200 lb by trimming the ballast to a total weight of 200 lb for test transducer and ballast.

HUNTER'S POINT FIELD MEASUREMENTS

Because the MIL-S-901D test specified only the initial conditions of the test; i.e., explosive weight and range, the magnitude and shape of the resulting shock wave and inertial impulse at the FSP had to be measured if we were to duplicate those conditions in a shock tube. So, in February 1987, we travelled to Hunter's Point to observe a shock test and determine what would be necessary to make field measurements of the shock wave pressures. After that, arrangements were made whereby we were given space to mount a gage on the transducer fixture and a dedicated data line to shore where we would set up our recorder during a subsequent test series.

The tests, normally carried out by the West Coast Shock Facility staff, included recording of the shock wave pressures at several points on the transducer mounting fixture beneath the FSP. The gages they used were the same type (tourmaline disks) that we had obtained originally from the Naval Ordnance Laboratory. Long cables of about 500 ft connected the gages to the recording instruments ashore. To minimize the loading effect of the cables, charge amplifiers were used to amplify the gage signals. The recording device was an instrumentation tape recorder. The high-frequency response of the charge amplifiers was limited to about 20 kHz. For this reason, as well as the bandwidth limitation imposed by the tape recording, we elected to use voltage amplifiers and to compute the cable loss from the ratio of impedances.

We first thought we would be able to place a preamplifier in the FSP and eliminate a large part of the line load. We considered several types of preamplifiers with adjustable or fixed gain. We finally chose the Ithaco Model 167 as the most probable candidate. It has unbalanced input and output, fixed 20 dB gain, 1 mΩ input impedance and 1 MHz maximum frequency response. We measured shock waveforms through the preamp both with the input unloaded and with a capacitive attenuator (C=19.7 nF). But, when the test was done, the input level with the gage unloaded proved much too large. The capacitive attenuator mentioned above attenuates the gage input approximately 20 dB, making the overall gain near unity, and simulates placing the preamp at the end of the long cable. In retrospect, working with the preamp near the gage instead of at the end of the cable might have had a slight advantage in reducing the crosstalk pickup from the line used to fire the charge and the radio station interference at Hunter's Point. This configuration was not tried because of the small number of trials available for experimenting at Hunter's Point. We were at a severe disadvantage by having only a few shots per year where we would be allowed to participate. In the final decision, the test manager had misgivings about placing active electronics in the FSP, and the preamp was not used to drive the long line.

During the West Coast Shock Facility test, the test shot sequence was made from ranges of 40, 30, 25, and 20 ft and the explosive was detonated at a depth greater than that of the gages. Because the standoff range was changed for each shot, the incidence angle was different for each shot. Our gages were tested for response to angled orientation. The results showed no large errors due to angled incidence, provided the disk faces were aligned parallel to the direction of the incoming shock wave. It was impractical to try to rig the gage axis for parallel incidence for each shot, so the gage was rigged parallel to the surface with the disk faces vertical to minimize the effect of the changing angles of incidence. This requirement underscores the need for a visual indicator of the crystal stack alignment within the gage.

The first trip to Hunter's Point for shock wave measurements was made in July 1987. We had two gages available for the trip. A special gage mount was made to hold the gage about 25 in forward of the transducer mounting plane. We planned this to avoid early reflections of the shock wave from other transducers mounted on the fixture. Figure 17 shows a sketch of the gage mount. The gage cable was connected to one of the West Coast Shock Facility data lines inside the FSP. Ashore, the data line was connected directly to the Nicolet oscilloscope. The total line and gage capacitance was 13.7 nF unbalanced.

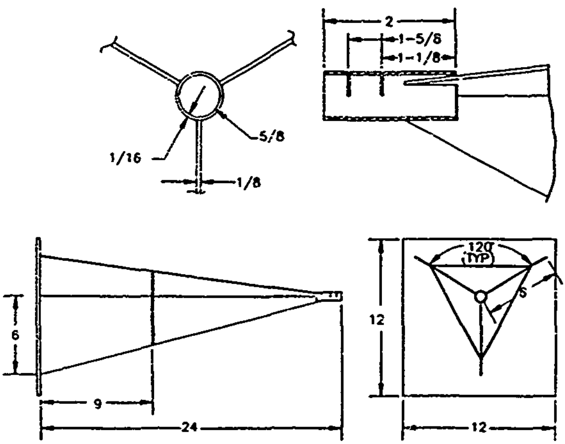

Fig. 17 - Sketch of FSP gage mount used at West Coast Shock Facility.

When the first shot of the series was fired, the Nicolet oscilloscope was triggered by the shot firing pulse and the gage output came too late to be recorded. Because the Nicolet oscilloscope is unable to create long post-trigger delay times (it has only one sweep generator), the only way to deal with the problem was to try to adjust the trigger level. A pair of photographs showing different stages of the water plume generated by the 20-ft shot may be seen in Fig. 18. When the FSP was retrieved, our gage appeared to be broken. There is some question as to whether it succumbed to the shock exposure, or whether it was struck by one of the mooring lines in the process of retrieval. Its projected position on our special mount made it quite vulnerable. For the subsequent shots, the second gage was fitted and a low-pass filter was installed at the Nicolet oscilloscope input. The filter was set to stop all frequencies above 250 kHz. The remaining three shots of the test series failed to trigger the oscilloscope, possibly because of the effectiveness of this filter, or because of the crudeness of the Nicolet's trigger level adjustments. The gage passed a squeeze test before each of the missed shots, so it is difficult to explain the failure to obtain the signal.

A representative from the Naval Undersea Warfare Center also was making shock wave measurements at the time using three PCB Series 138A tourmaline gages like the ones we had tested. He recorded these gage outputs on magnetic tape. We were able to copy his tape playback using the Nicolet oscilloscope and thus obtained some data from the test. So, the first trip to Hunter's Point ended without any of our own data being recorded. Valuable experience was gained, however, and we were able to plan our next data-gathering trip with more confidence.

It seemed to us that interference and crosstalk in our data line was the primary reason for the failure to obtain data. The data line should be isolated from sources of interference as much as possible. The primary sources were a nearby AM radio station and the high-voltage pulse used to fire the detonator of the explosive charge. The firing line was electrically isolated and shielded, but it ran in close proximity to the data lines. We decided to provide our own data line and to isolate it as thoroughly as possible from all other lines. For us to be able to change gages, it was necessary to make one pair of connections in the interior of the FSP. Otherwise, the conductors were unbroken from the FSP to our recorder input. To solve the problem of introducing long delay time in case of premature triggering, we decided to use a Soltec waveform digitizer, which allows using two sweep rates on the same trace. A long delay can be introduced before the sweep is speeded up to provide increased time resolution for the data of interest. The Soltec digitizer is also capable of storing more than a hundred times as many data points per trace as the Nicolet.

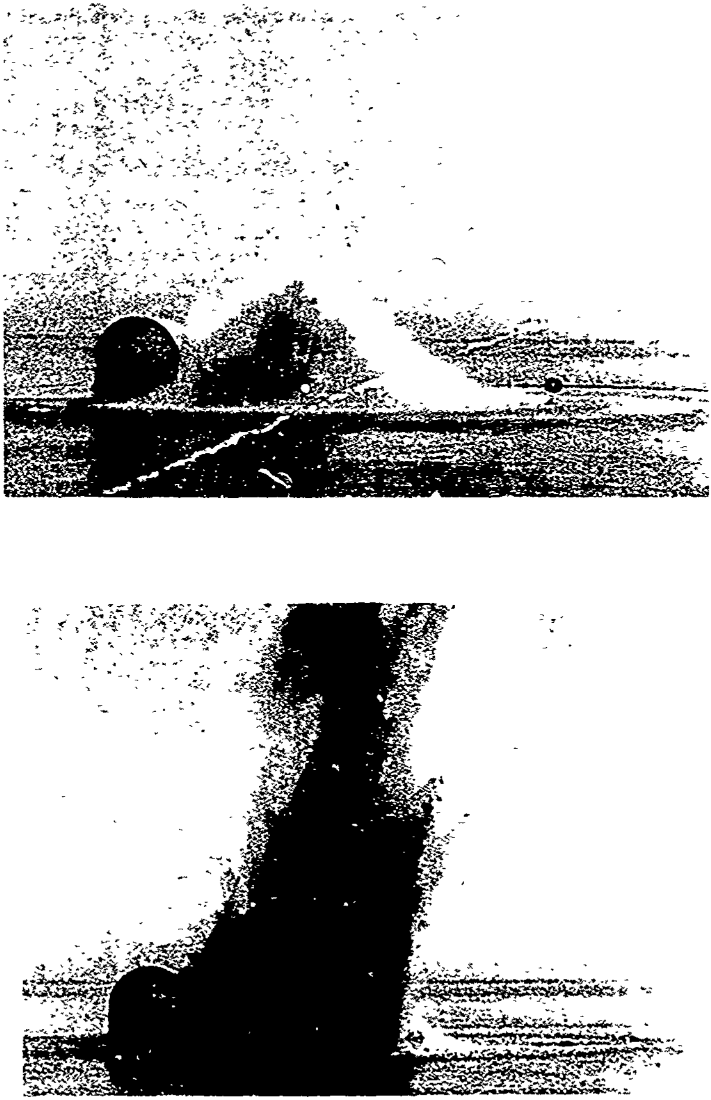

Fig. 18 - 20-ft-range test shot at West Coast Shock Facility.

After returning to Orlando, we began testing to select a cable type for our own data line for the next trip. Six types of coaxial cable were tested:

Belden 8428
Belden 9223
Belden 9394
Belden 9778
Times Wire MI 41126
Envirocon white Teflon

We submerged a 6-ft piece of each type of cable and connected the end to an Endevco 2740B charge amplifier. The cable was hung vertically in the water and a blasting cap was detonated one foot to the side of its midpoint. The Times Wire MI 41126 proved to be the quietest cable by a large margin. This is the same type that was used on the blast gages made at the Naval Ordnance Laboratory. The low-noise data cable used at the West Coast Shock Facility was Times Wire MI 31594. It is a similar cable of 2-conductor shielded construction and gave the West Coast Shock Facility the option of running the data lines balanced or unbalanced. Our gages were constructed to be used unbalanced, so the coaxial cable was a simpler solution for us.

We then set up a test to see if the Soltec digitizer could produce the long delay required to record the blast gage data when the crosstalk from the shot-firing pulse was large enough to trigger the digitizer. To simulate crosstalk, we triggered the Soltec directly from the battery used to fire a blasting cap. The delaying sweep rate was set to 1 ms per sample, and the expanded sweep rate was 1 μs per sample. We had no problem adjusting the number of samples so that the time window of interest was captured without having an absurdly large number of samples to deal with.

In February 1988, we attended a course on response of marine structures to underwater explosions. We used material presented in that course to compute the vertical kickoff velocity of the FSP. The computation yielded a value of 10.7 ft/s, which is quite close to the value measured by the West Coast Shock Facility.

The second trip to Hunter's Point was to take place in August 1988, and we began to prepare by assembling seven tourmaline gages which were either new or rebuilt. Each gage head was molded to approximately 30 ft of Times Wire MI 41126 low-noise cable. Calibrations were done using the method described earlier. The gages were graded according to the quality of their transient response.

We used the same gage mount that we had used the year before. Shortly before the date of the test, the gages, cable, and recording equipment were shipped to California. Several days were allotted before the tests for setting up and testing the equipment.

The 20-ft-standoff shot was the most important to us, because it is the one we are simulating in the shock tube. We reasoned that if gages were likely to be damaged during the tests, we should retain our best gages for the last shot. A gage with less than the best waveform response was, therefore, mounted first; its cable was connected to our data line in the FSP. The FSP was located on shore at the time. When all the other test devices were mounted and checked, the FSP was lifted by large cranes and placed in the water. The end of our data cable came directly into the small trailer that we were allowed to use for recording. There we connected the cable to an Ithaco Model 4302 Dual Filter, using only half the filter. The output of the filter fanned out into a Nicolet Digital Oscilloscope, a Soltec Waveform Digitizer, and a Honeywell Model 101 Instrumentation Tape Recorder. The Honeywell recorder was powered from a large Xentec isolation transformer. The gage-cable capacitance and conductance were monitored repeatedly while the FSP was on shore. After the FSP was launched, those would be the only tests we could perform to determine the integrity of the gage.

The Soltec recorder was programmed for a large time delay, in case the firing pulse interference was large enough to trigger the recorder. The Nicolet oscilloscope was set to be triggered by the shock wave pressure pulse, and the Honeywell recorder was running as a backup log in case both digitizers failed to catch the data.

Figure 19 is a drawing showing the depths, range, and other dimensions for the 40-ft shot. The computed maximum bubble radius is also drawn for comparison. The Soltec recorder captured the data on the first shot. The Honeywell recorder had developed a bad head preamp sometime between the last checkout and the test shot. The waveform from the Soltec recorder was very clean and immediately usable. The FSP was retrieved and prepared for the second shot, the 30-ft shot, which would be fired the next day. We decided to change to a better gage, even though the first shot did not damage the gage. The same equipment configuration was used. The second shot was also captured successfully by the Soltec.

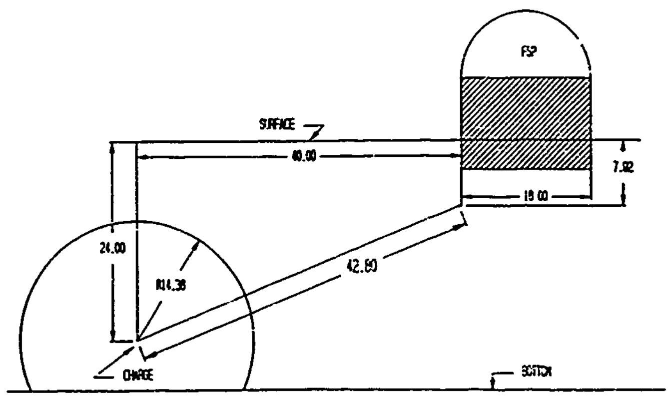

Fig. 19 - Diagram of 40-ft test at West Coast Shock Facility - Aug. 8, 1988.

For the third day's shot at 25 ft, we fitted a different gage which we thought would give better waveforms. We were allowing the Soltec recorder to trigger from the firing pulse crosstalk, so it was unlikely that we would miss the time period of the shock wave response. This time the Soltec captured a trace that looked like it had the proper shape, but it was only a fraction of the expected amplitude. We were completely puzzled by this result, especially since a quick check of the West Coast Shock Facility recordings revealed normal levels for the pressure pulse. A leakage test of the gage showed nothing unusual. On the fourth shot, the gage failed to produce any output. The crosstalk signal was still there and it triggered the Soltec recorder normally, but there was no signal in the time period where the shock wave response should have been.

When we computed the peak pressures for the shots that we recorded successfully (40 ft and 30 ft), the numbers were slightly higher than the similarity equation yields for HBX-1. When we received the West Coast Shock Facility measurements for the same shots, we saw that theirs were very much higher. The table below shows the West Coast Shock Facility measurements, our measurements, and the HBX-1 scaling law results compared.

Table 1 -

	Shot 1 (psi)	Δp%	Shot 2 (psi)	Δp%
WCSF	2368	+63	3070	+61
USRD	1715	+18	2087	+10
HBX-1	1449	---	1901	---

It is possible that two phenomena are affecting the West Coast Shock Facility results. The close placement of the gages to the hull of the FSP and other instruments on the test fixture could cause early reflections to be superimposed on the shock wave pressure pulse at the gage The extreme low-cutoff filter frequency used in their recording technique would then smear these artifacts into the shock pulse and make the peaks appear higher. Secondly, the explosive charge is detonated very near the bottom, and even the fuzzy interface produced by the mud will affect the presumption of spherical spreading. An increase in the pressure amplitude by reflected energy will probably be the result. This effect would be seen in our measurement, too.

IDEAS FOR FUTURE DEVELOPMENT

It is evident from our experiences at Hunter's Point that our gages have not been developed to the point of complete confidence. Durability seems to be their weak point.

The concept of the distributed breech has some merit, and might be developed as a means of reducing the problems of fracturing breech blocks and deforming of the small-diameter shock tube sections. No specific designs are in hand, but ideas proceed along the lines of a simple planar array of blasting caps.

The existing 6-in. shock tube can be expanded to accommodate larger transducers for a very modest investment. Drawings have been made for a conical section extended to 10-in. diam and a new 10-in. slider and cylindrical section. This modification would allow us to obtain more data on the inertial performance and improve our confidence in designing the inertial section for a 20-in. shock tube.

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